Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 81 (2019) 1354–1359

www.elsevier.com/locate/procedia

52nd CIRP Conference on Manufacturing Systems

The Carbon Footprint of Manufacturing Digitalization: critical literature review and future research agenda

John Patsavellas[a]*, Konstantinos Salonitis[a]

[a]Manufacturing Theme, Cranfield Univeristy, Cranfield, Bedfordshire, MK43 0AL, England., UK

* Corresponding author. Tel.: +44 1234 75 4589. *E-mail address:* john.patsavellas@cranfield.ac.uk

Abstract

As the world of manufacturing is accelerating to its digital paradigm, it could become a significant generator of energy-consuming data. The storage of such data is facilitated by the proliferation of easily accessible cloud services, whilst the cost of transmission and storage has significantly dropped. Within a sustainability context, the carbon-footprint characteristics of these masses of data-capture, transmission, storage and management have not been given adequate due-diligence. A cause of this omission may be the assumption that renewable forms of energy generation and storage, may eventually render the big cloud data-centers carbon neutral. However, such assumptions may be pre-mature and not synchronized with unfolding realities, as the carbon footprint implications of the industry 4.0 discourse have not been assessed. This paper ascertains the absence of any structured assessment framework of CO_2 emissions of the various components of industrial digitalization, as an evaluation tool of the accelerating digital transformation of manufacturing within a sustainable growth context.

Keywords: digital transformation; industry 4.0; carbon footprint; connected stack; energy efficiency; IoT; IIoT;

1. Introduction

The digital transformation of the manufacturing sector along with its hype of ubiquitous buzzwords such as Industrial Internet of Things (IIoT), smart manufacturing, Digital Twins and Industry 4.0 is a phenomenon of our time, lauding the possibilities of a new technological revolution. Indeed, manufacturing has experienced many waves of excitement in its recent history, fueled by many terms and acronyms referring to tools and philosophies in the cornucopia of fashionable "panaceas" such as JIT, lean, TQM, Six-Sigma and Agile to name but a few.

The arrival of smartphones with mobile internet and fast fixed broadband, has transformed the way people work, communicate and consume information in very profound ways. This has been enabled by notable advances in cellular networking, miniaturized sensors, new internet connection protocols as well as a proliferation of mobile software applications. From the emergence of the first iPhone in 2007, the adoption of mobile internet has been exponential [1]. This had an impact on the deployment of sensors, triggering a "sensor tornado from 10 million sensors in 2007 to 15 billion micro-electro-mechanical system (MEMS) sensors in 2015" [1]. These sensors have enabled the Internet of Things (IoT), in which they act as converters of physical object attributes into representative digital data in the virtual world. The data captured by the MEMS of the IoT, is used to monitor and control the functions and interactions of these objects and is transmitted via internet protocol to the "Edge" or the "Cloud", essentially data warehouses, where the data is stored, categorized, analyzed and retrieved from, on demand. This new technological capability, along with the advent of smartphones and the unstoppable march of internet video streaming, has been generating enormous amounts of data which in turn is leading to a building boom of new data centers around the world. The corresponding data headline numbers and forecasted growth estimates are truly impressive in magnitude. Ninety percent of all data today was created in the last two years

2212-8271 © 2019 The Authors. Published by Elsevier Ltd.

10.1016/j.procir.2019.04.026

with a daily estimate of data generation at 2.5 quintillion bytes [2] (2.5 Exabyte- an Exabyte being 10^{18} bytes). By 2020, it is estimated that for every person on earth, 1.7 MB of data will be created in the duration of every single second [3]. The evolution of these new technological capabilities has helped with the emergence of the fourth Industrial revolution concept (Fig. 1), aptly named Industry 4.0. Its premise is that Cyber-Physical Systems (CPS), comprising of interconnected smart machines, storage systems and production facilities, will be capable of autonomously exchanging information, triggering actions and controlling each other independently [4].

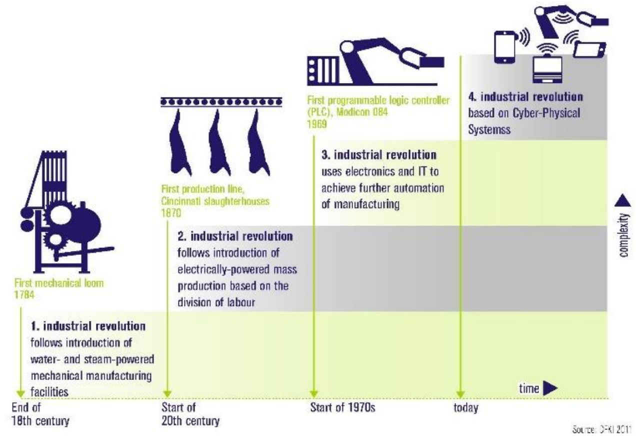

Fig.1. Industry 4.0 [4].

The Industry 4.0 concept however, goes beyond CPS in that the new data connecting technologies based on IP protocols, can provide effective connections of the modern enterprise's critical enterprise software platforms. Such connections in manufacturing businesses have hitherto been very expensive, complex and piecemeal, due to the incompatibility of their legacy origins; meaning that in most manufacturing enterprises, the software systems capturing, transmitting and controlling key information are distinct layers of functional "islands" of data. This in turn, traditionally meant the deployment of manually generated spreadsheets and paper printouts with people acting as the connecting nodes of such data between different layers of the software stack that is needed to run a modern enterprise. Fig. 2 is a simplified depiction of the stack of enterprise software automation, which the new technologies are now able to integrate digitally together, via a "broker" server using a "lightweight" protocol such as MQTT.

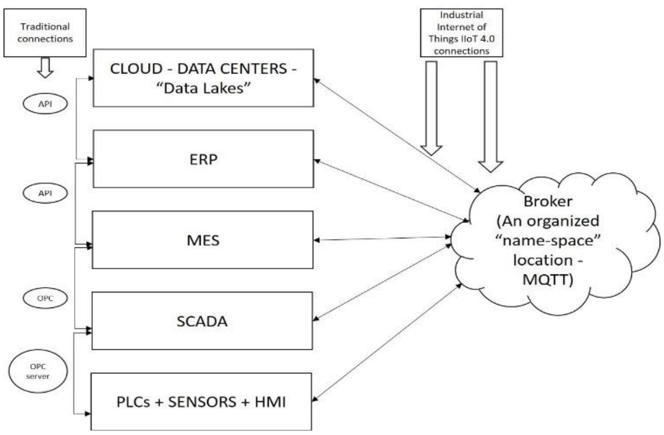

Fig. 2. The 5-Layer Model of Automation – The Automation Stack [5].

As new connection protocol standards, such as OPC UA (Open Platform Communication Unified Architecture) and MQTT can enable low cost seamless integration of information between hitherto incompatible systems, even small companies can achieve smooth "plug and play" 4.0 integration of their IT systems with their Operational Technology (OT) systems [6]. Increased development and supply of MEMS has also resulted in the substantial cost reduction of sensors with an average cost of IoT sensors now already below $0.50 each as seen in Fig. 3 [7,8].

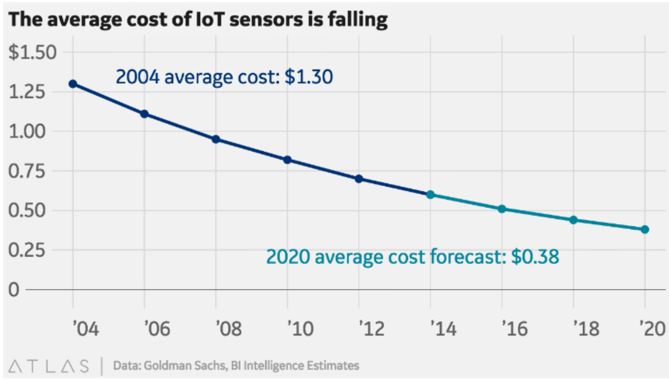

Fig. 3. The plummeting cost of MEMS sensors [8].

Indeed, this also means that manufacturers do not have to disregard older machines in their OT infrastructure. Through retrofitting with smart sensors that collect comprehensive data in real time, they can integrate "dumb" machines with new "smart" equipment and their planning, control and ERP systems [7]. Such digital transformation of manufacturing is purported to be impactful in terms of higher efficiency, flexibility and responsiveness, transforming factories from traditional cost centres into highly optimised plants in their usage of material inputs and energy [9]. Studies in Germany estimate that Industry 4.0 can deliver annual manufacturing efficiency gains of between 6 and 8 percent [10], and the Germany Digital Strategy 2025 report (2016) [11] projects productivity gains of up to 30 percent by 2025. In the UK, government commissioned studies have opined that the positive impact of faster innovation and adoption of Industrial Digital Technologies in the manufacturing sector, could be as much as £455 billion over the next decade, increasing sector growth between 1.5 and 3 percent per annum, whilst improving productivity by more than 25 percent by 2025 [12]. Another prevailing view across most reports is that since manufacturers lead other sectors in R&D investment, given the higher productivity enabled by digital integration, they will be more prone to invest in more advanced automation thus leading to higher levels of competitiveness and flexibility [9], [13]. Coupled with a predicted drop in the cost of industrial robotics of approximately 10 percent per annum and further advances in MEMS and artificial intelligence (AI) allowing the potential use of robots in complex environments and tasks, the likelihood of accelerated technology deployment could be indeed high [9], [14]. Furthermore, efforts of institutions like the OPC foundation to provide guidance and standards in industrial communications is seen as an encouraging factor. [6], [15]

1.1. The question of CO_2 emissions of the digital transformation of manufacturing

As manufacturing goes through its digital transformation, connecting all its IT and OT with data-generating sensors, and transmitting this data to the “Edge” or the “Cloud”, electrical energy will be required to power it. According to the International Energy Agency (IEA), industries already account for a major share of global electricity consumption – amounting in 2014 to 42.5 % worldwide [16] – and energy networks need to accommodate any growth in electricity demand from industrial consumers.

Ostensibly, this gives cause to consider the magnitude of energy required to power up the potentially vast amounts of data that connected industrial elements will be generating, transmitting, consuming, storing, analyzing, retrieving and retransmitting. This would include the carbon emissions by the whole industrial landscape of devices that will have sensing, processing, and communication capabilities. Whilst the insatiable human appetite for more data-transmission and generation is driving the need for more power-hungry data centers, where ultimately the majority of all this new data would be hosted, the question of what would the impact of the digital transformation of manufacturing be on the threatening rise of global CO_2 emissions is of legitimate interest.

2. Literature review

In an attempt to answer the question of the energy and carbon footprint impact of the digital transformation of manufacturing, a literature search was undertaken to establish a baseline of evidence. The survey revealed aspects of the energy and CO_2 footprint of the information and communication technology (ICT) sector but with little or no reference on the contribution of Industry 4.0 and digital manufacturing, although there is tacit recognition of its potential role in the landscape of global digitalization as per Figure 4.

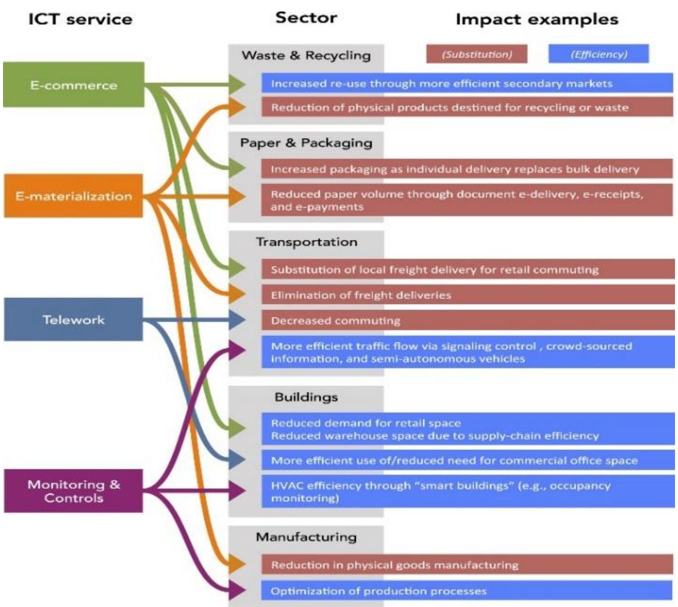

Fig. 4. Relationships among ICT service types, economic sectors, and impacts [17].

Somewhat surprisingly, there are also very few studies on the overall CO_2 of the total global ICT sector. Only four published studies with notably variable results can be found on the subject [18]. In addition, all four of them admit that forecasting the possible future contribution of the IoT contribution to the global carbon footprint has not been included holistically [18], [19], [20], [21]. Only the usage estimates of CO_2 emissions of powering the hardware has been addressed, excluding the data-transmission phase, with expressed uncertainty on the taxonomical relevance IoT (and therefore by implication the IIoT) in the realm of ICT [19]. It is shown [18] that the march of ICT growth will have a real impact on the proportion of CO_2 emissions worldwide as shown in Fig. 5.

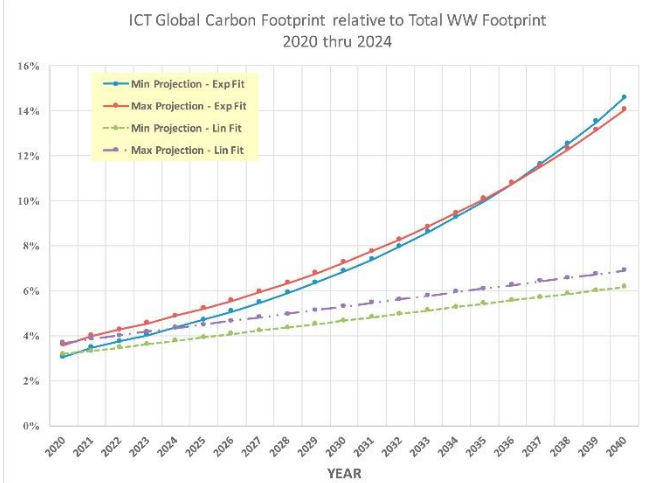

Fig. 5. ICT footprint as a percentage of total footprint projected through 2040 using both an exponential and linear fits [18].

These growth estimates are in the backdrop of growing sales of semiconductors and integrated circuits, which for the first time in the history have reached the 1 trillion mark in 2018 as shown in Fig. 6.

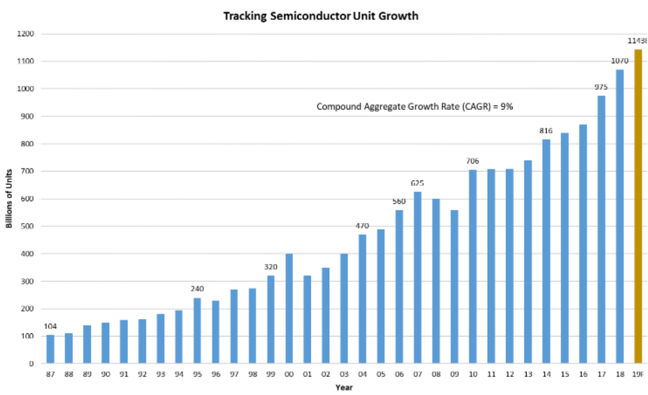

Fig. 6. Semiconductor growth has finally broken the 1 trillion mark [22].

A small number of articles have attempted to address the energy load of data transmission in relation to the possible network architecture and IIoT communication protocols for the sensor nodes and the overall network in industrial settings of Industry 4.0. [23], [24], [6]. Some as per Wang et al. [24], have reported robust energy usage reductions on network designs that utilize hierarchical control and "sleep" and "wake-up" signals for sensor nodes using an optimization algorithm that sifts through non-critical data streams and queries. Fig. 7 summarizes their experimental results of a controlled 300-node industrial network trial, showing that when deploying predicted "sleep intervals" for switching the transmitting nodes, resource utilization increases across time (a) whilst energy consumption dramatically decreases (b), particularly as the amount of nodes increases. Such methods of network optimization could hold good promise for carbon footprint minimization as the adoption of Industry 4.0 scales up.

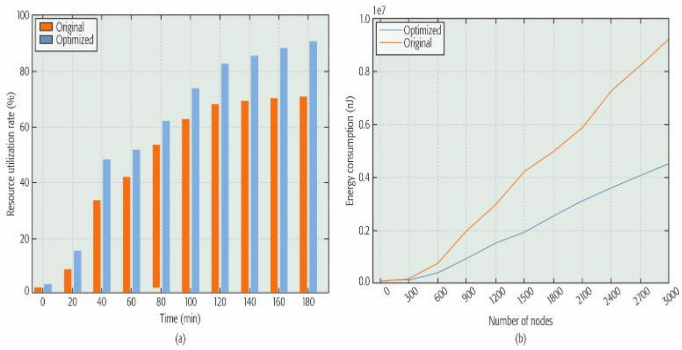

Fig. 7. Experimental results of resource and energy optimization – Green IIoT [24].

One commonly held aspiration of the digitalization of manufacturing was the hope that the deployment of digital technologies such as the IIoT, would facilitate the reduction of energy usage in factories, by reducing resource consumption and carbon emissions of industrial systems [24]. By getting a stream of data representing the real-time energy usage of each individual plant and process, manufacturing professionals would be able to assess hitherto unseen losses and reduce wasted energy (e.g. by turning equipment to "sleep" mode, or off, when not in use). However, although there have been reports of energy cost savings in audits carried out in the USA and Australia [24] no actual known studies have reported on any aggregated results of any associated global CO_2 emission reduction.

It is also notable that the debate of whether the energy impact of ICT across all sectors is overall a net positive or negative, is raging both in the press and in academic literature. Pertinent meta-analyses of the academic work supporting either end of the spectrum, was carried out by Horner et al. [17] and Bieser and Hilty [21]. Some of the key findings of these analyses are that other than the inherent complexities involved in CO_2 emissions estimations, those studies also face methodological challenges, regarding the definition of system boundaries, interaction among use cases and "rebound effects", which together pose a huge challenge in judging the significance and comparability of results [26].

Belkhir and Elmeligi [18] have stipulated that the two largest contributors of Carbon emissions in the ICT sector are Data Centers (usage phase) and Communication Networks (data transmission phase). However, although they also did not include the digitalization of the manufacturing sector as part of ICT, their findings provide an informative paradigm of the key sources of carbon footprint in digitalization that could be used as an informative platform of assessment for manufacturing.

Malmodin and Lunden [19] in their most recent study have elaborated that although they have not included IIoT and industry in general, in their taxonomy of the ICT & Entertainment and Media (EM) sectors, they have nevertheless modelled a large amount of IoT sensors in their study of future CO_2 emissions – albeit only in their energy usage phase. Their conclusion was that even at a large scale of deployment (500 billion IoT sensors), their CO_2 emissions impact is relatively small as shown in Fig. 8.

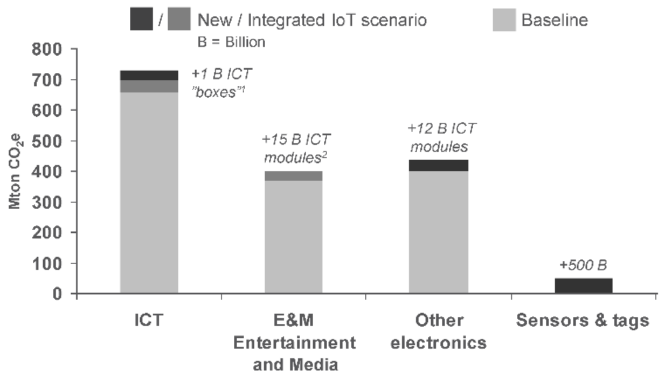

Fig. 8. A future IoT scenario: 500 Billion IoT Sensors [19].

The projections by Malmodin and Lunden [19] in Figure 7, can be further contextualized given that a lot of the MEMS sensors in the IIoT of manufacturing digitalization might be powered mostly with batteries [24], or indeed by energy-harvesting available ambient EMF in dense industrial environments. However, given the findings of Belkhir and Elmeligi [18], the energy payload will be in the transmission phase of data, to and from the servers in the "broker" node of the IIoT network as well as to and from any remote Cloud Data Center locations, where the data will be most likely stored and accumulated. In the work published by Andrae and Edler [19] despite the Data Centers' drive to utilizing renewable power and increasing their efficiencies, an average of 25% annual growth in Global Data Center IP Traffic means that they are still likely to be using up to 13% of the global electricity in 2030 compared with 1% in 2010. Andrae and Edler's [20] worst-case predicted scenario that the ICT sector could be using as much as 51% of global electricity in 2030 and contributing up to 23% of the globally released CO2 emission is a indeed a sobering one when it comes to impact on climate change.

3. Future research agenda

This section offers suggestions for the future research agenda regarding the carbon footprint of manufacturing digitalization. Since there are no such focused scholarly studies forming a baseline in the manufacturing sector, a similar methodology of data collection and aggregation as that used by studies in the ICT sector should be proposed [18]. That would ascertain the impact of Industry 4.0 and IIoT on global greenhouse gas emissions (GHGGE), will give further clarity on the prospects of sustainable growth in manufacturing through digitalization.

3.1. Scope of the research agenda

In order to achieve a coherent system-based outcome from future studies, only the critical enabling elements of the manufacturing digitalization ecosystem should be encompassed. This is composed by four broad system components; namely (i) the MEMS sensors enabling the IIoT; (ii) the hardware of the 5-layer model of the automation stack, see Fig. 2,- including enterprise software computers and servers, local data-lake (“Edge”) storage servers, programmable logic controllers (PLCs), human-machine interface (HMI) devices, and advanced robotics and flexible automation; (iii) the data exchange communication networks - including internal and external connecting hardware and services, and (iv) the remote data centers that will accumulate and store all generated data.

3.2. Proposed research methods

Following the approach of the ICT sector [17], [18], [20] relevant data on the following key factors should be obtained:

- Production Energy (PE) of all elements in the scope.
- Useful Life (UL) of each element.
- Use Phase Energy (UPE) per year of UL.
- Quantity of installed elements.
- CO_2 footprint of each element aggregated for each of the four broad categories of the recommended scope.

The relevant data may be obtained from globally reported data on manufacturing plant installations and annual shipments of relevant scope devices. All data could then be aggregated and presented in a “merimekko”-type chart that can depict the whole system impact in one summary graph, as per example in Fig. 9. Annual growth rates can be estimated from this analysis to obtain forward projections of CO_2 emissions due to the ongoing digitalization in manufacturing which is destined to take a number of years.

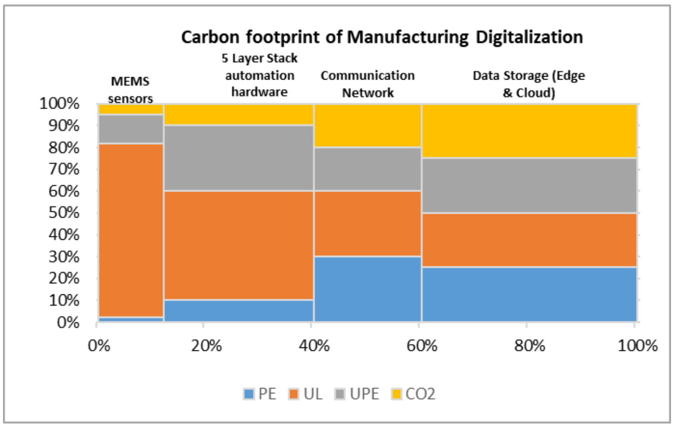

Fig. 9. Example of graphic representation of aggregated data.

4. Conclusion

There is notable absence of peer-reviewed published work in relation to the possible emissions from the impending 4th industrial revolution that will involve the Industrial Internet of Things and generation of large volume of data destined to be transmitted to Cloud Data Centers. The impetus for the digital transformation of manufacturing is mounting and the technology to make it a reality is becoming ubiquitous and affordable. Given that even for the ICT sector the complexities of estimating the future carbon net-effect of increased data generation and digitalization are great, it would be prudent to ensure that companies, governments and institutions should drive towards a carbon-neutral goal, within an agreed standardized framework of best practice. This could even be brought to fruition as part of an update to international sustainability standards facilitated by UNIDO and relevant standards bodies. The evidence of the existing studies on the growth of data generating sources and the potential merit that such data can have when turned into intelligent insights that can be acted upon automatically in manufacturing, calls for action in transparency of its carbon impact. We have set out a future research agenda with a clear scope and structure, focusing solely on the landscape of manufacturing digitalization, based on similar scholarly studies in the ICT sector. Further work in developing relevant standard frameworks as kite-marks of transparency for assessing carbon emissions and deploying “plug-and-play” carbon-neutral digitally connected systems in manufacturing, can enable sustainable deployment of Industry 4.0. This is a “smart” imperative if the aspirations of clean growth [15] through “smart” manufacturing digitalization are to be realized.

Acknowledgements

Walker Reynolds, President of Intellic Integration, Irving, TX USA is acknowledged for inspiration and his permission to use elements of his whiteboard schematics from his video series on enterprise integration.

References

[1] Colin Johnson, C. (2015) "Roadmap to Trillion Sensors Forks", *EE Times*, Available at: https://www.eetimes.com/document.asp?doc_id=1328466# [Accessed: 11 January 2019]
[2] DOMO Inc (2017) *Data Never Sleeps 5.0*. Available at: https://www.domo.com/learn/data-never-sleeps-5?aid=ogsm072517_1&sf100871281=1 [Accessed: 9 February 2019]
[3] DOMO Inc (2018) Data Never Sleeps 6.0 (2018). Available at: https://www.domo.com/learn/data-never-sleeps-6 [Accessed: 9 February 2019]
[4] Kagermann, H., Wahlster, W. and Helbig, J. (2013) Industrie 4.0. Available at: https://www.iosb.fraunhofer.de/servlet/is/24313/Final_report__Industrie_4.0_accessible.pdf?command=downloadContent&filename=Final_report_Industrie_4.0_accessible.pdf [Accessed 10 February 2019]
[5] The 5-Layer Model of Automation – The Automation Stack (Adapted by permission from Walker Reynolds Intellic Integration, “The Automation Stack”) [Video] Available at: https://youtu.be/3u2cRRMlG7Q [Accessed 15 January 2019]
[6] Drahoš, Peter & Kucera, Erik & Haffner, Oto & Stark, Erich. (2018). Industrial Communication and Industry 4.0.
[7] Microsoft Dynamics 365 (2019) *Manufacturing Trends Report 2019* Available at: https://info.microsoft.com/ww-landing-DynOps-Manufacturing-Trends-eBook.html [Accessed 25 January 2019]
[8] Goldman Sachs (2016) *BI Itelligence Estimates*, Altas 2016, Cost of Sensors Graph Available at: https://www.theatlas.com/charts/BJsmCFAl
[9] Castillo, Pilar del. MEP, Industry , Energy and Reserach Committee (ITRE) 2016. "Smart Manufacturing". European Energy Innovation. Spring 2016.

36-37. http://www.europeanenergyinnovation.eu/OnlinePublication/Spring2016/mobile/index.html#p=36 [accessed 5 February 2019]
[10] Smart Service Welt Working Group/acatech (Eds.): Smart Service Welt – Recommendations for the Strategic Initiative Web-based Services for Businesses. Final Report, Berlin, March 2015. Available at: https://www.eitdigital.eu/fileadmin/files/2015/publications/acatech_report_SmartServiceWelt2015_full_en.pdf [Accessed 31 January 2019]
[11] Digital Strategy 2025 Report, April 2016, DE Digital, Federal Ministry for Economic Affairs and Energy. Available at: https://www.de.digital/DIGITAL/Redaktion/EN/Publikation/digital-strategy-2025.html [Accessed: 25 January 2019]
[12] Made Smarter Review, UK Gov Report , 2017. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/655570/20171027_MadeSmarter_FINAL_DIGITAL.pdf [Accessed 5 February 2019]
[13] World Economic Forum (2018) The Readiness for the Future of Production Report 2018. Available at: http://wef.ch/fopreadiness18 [Accessed: 31 January 2019]
[14] Industry 4.0 after the initial hype – Report, McKinsey 2016. Available at: https://www.mckinsey.com/~/media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/getting%20the%20most%20out%20of%20industry%204%200/mckinsey_industry_40_2016.ashx [Accessed 21 January 2019]
[15] OPC UA: Interoperability for Industrie 4.0 and the Internet of Things New Edition v7. [online]. [cit. 2018-01-20]. https://opcfoundation.org/resources/brochures/
[16] UNIDO (2017). Accelerating clean energy through Industry 4.0: manufacturing the next revolution. Nagasawa, T., Pillay, C., Beier, G., Fritzsche, K., Pougel, F., Takama, T., The, K., Bobashev, I. A report of the United Nations Industrial Development Organization, Vienna, Austria.
[17] Horner, N. C., Shehabi, A., Azevedo, I. L. (2016)' Known unknowns: indirect energy effects of information and communication technology', Environmental Research Letters, Volume 11, Number 10
[18] Belkhir, L., Elmeligi, A., 'Assessing ICT global emissions footprint:Trends to 2040 & recommendations', Journal of Cleaner Production, Volume 177, 2018, Pages 448-463, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2017.12.239.
[19] Malmodin, J.; Lundén, D. The Energy and Carbon Footprint of the Global ICT and E&M Sectors 2010–2015. *Sustainability* **2018**, *10*, 3027
[20] Andrae, Anders & Edler, Tomas. (2015). On Global Electricity Usage of Communication Technology: Trends to 2030. Challenges. 6. 117-157. 10.3390/challe6010117
[21] Bieser, J.C.T., Hilty, L.M. (2018). Assessing Indirect Environmental Effects of Information and Communication Technology (ICT): A Systematic Literature Review. Sustainability. 10. 2662. 10.3390/su10082662.
[22] McClean Report http://www.icinsights.com/news/bulletins/Semiconductor-Unit-Shipments-Exceeded-1-Trillion-Devices-In-2018/ [Accessed 4 February 2019]
[23] M. Iglesias-Urkia, A. Orive, M. Barcelo, A. Moran, J. Bilbao and A. Urbieta, "Towards a lightweight protocol for Industry 4.0: An implementation based benchmark," *2017 IEEE International Workshop of Electronics, Control, Measurement, Signals and their Application to Mechatronics (ECMSM)*, Donostia-San Sebastian, 2017, pp. 1-6. doi: 10.1109/ECMSM.2017.7945894
[24] K. Wang, Y. Wang, Y. Sun, S. Guo and J. Wu, "Green Industrial Internet of Things Architecture: An Energy-Efficient Perspective," in IEEE Communications Magazine, vol. 54, no. 12, pp. 48-54, December 2016. doi: 10.1109/MCOM.2016.1600399CM
[25] IEA "Digitalisation and Energy 2017" Report". Available at: https://www.iea.org/digital/#section-1-4 [Accessed 9 February 2019]
[26] Bieser, J.C.T., Hilty, L.M. Indirect Effects of the Digital Transformation on Environmental Sustainability Methodological Challenges in Assessing the Greenhouse Gas Abatement Potential of ICT. In EPiC Series in Computing, ICT4S2018, Proceedings of the 5th International Conference on Information and Communication Technology for Sustainability, Toronto, ON, Canada, 15–17 May 2018; EasyChair: Manchester, UK; Volume 52, pp. 68–81.

2019-06-24

The carbon footprint of manufacturing digitalization: Critical literature review and future research agenda

Patsavellas, John

Elsevier

Patsavellas J, Salonitis K. The carbon footprint of manufacturing digitalization: Critical literature review and future research agenda. Procedia CIRP, Volume 81, 2019, pp. 1354-1359
https://doi.org/10.1016/j.procir.2019.04.026